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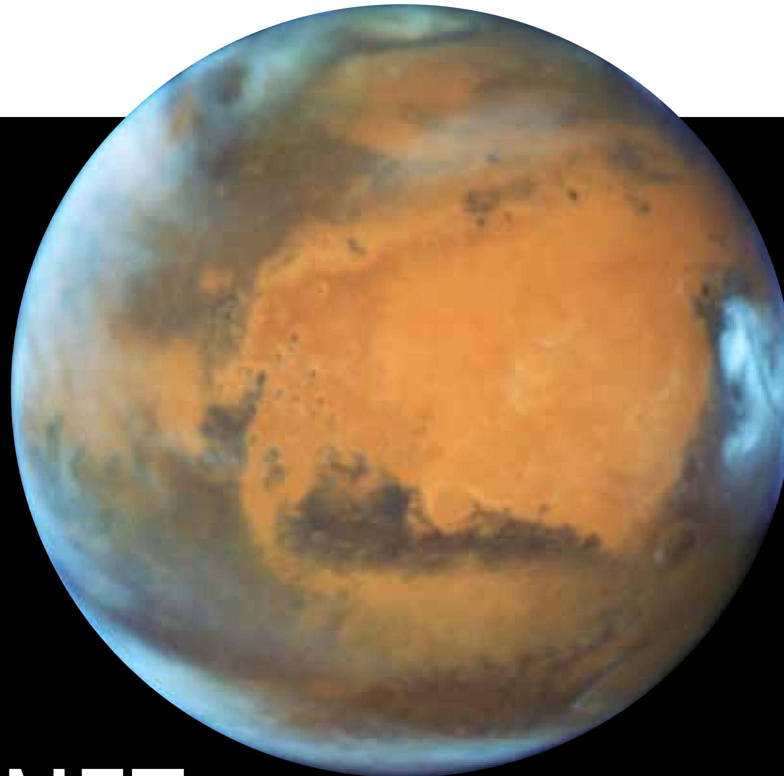

MARS
EXPLORING THE RED PLANET

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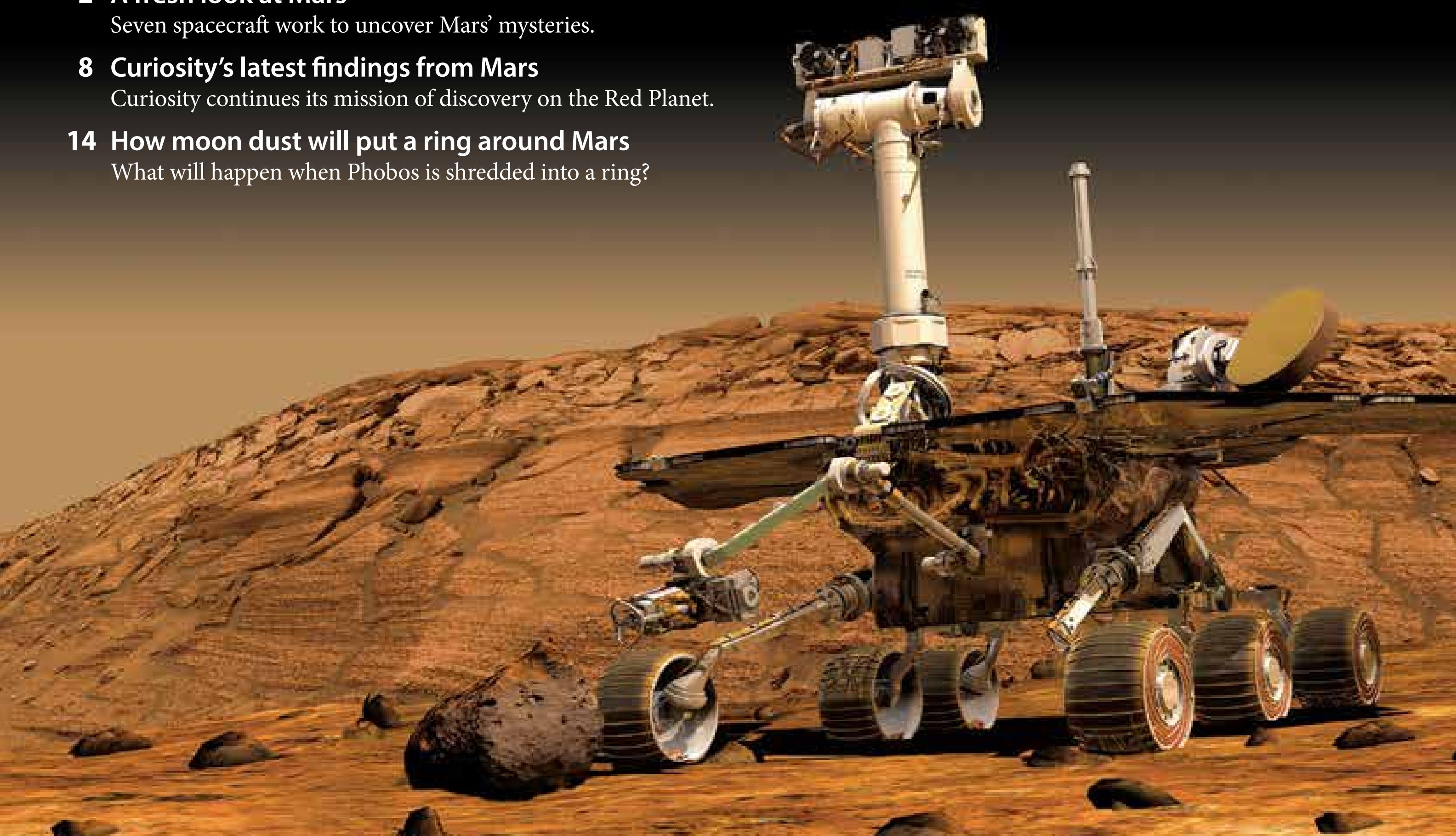


MARS: NASA, ESA, THE HUBBLE HERITAGE TEAM (STSCI/AURA), J. BELL (ASU), AND M. WOLFF (SPACE SCIENCE INSTITUTE); ROVER: NASA

A fresh look at MARS

Seven spacecraft — two on the ground and five circling above — continue to scour the Red Planet for signs of ancient water and conditions conducive to life.

by Jim Bell

Mars— the latest international hotspot. Although that designation might seem a bit far-fetched, it seems less so if you consider the seven spacecraft now operating at the Red Planet and the five more being readied to go as scientific tourists. Robotic emissaries from Earth have occupied Mars continuously since 1997, and the missions currently active date back to 2001. This is the busiest, most fruitful, and most exciting time in the history of Mars exploration. The armada of spacecraft delivers a steady stream of data to planetary scientists that has led to important discoveries but also raised intriguing new mysteries.

The ground truth

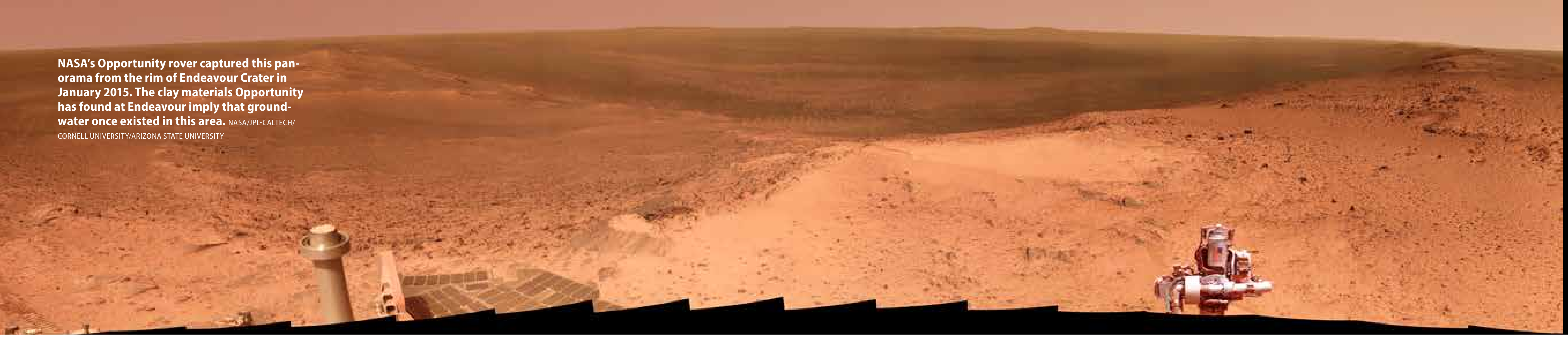
Two rovers — Opportunity and Curiosity — continue to return sensational scientific information from the surface. Opportunity, which landed in January 2004 and celebrated its 4,000th martian day, or sol (one sol equals about 1.03 Earth days), in April 2015, surpassed the 26.219-mile (42.195 kilometers) distance of a marathon a month earlier. The rover's science team, working on the planet's surface virtually through the robot, is now exploring the eroded rim of an ancient impact crater called Endeavour.

NASA orbiters previously had detected evidence for clay minerals on the rim of this 14-mile-wide (22km) crater. Opportunity has sampled those clays and found abundant evidence for mineral-filled veins containing gypsum. Both substances provide further proof that groundwater and perhaps even surface water once existed on this part of Mars. The clays, in particular, suggest that some of this water could have been comparable to fresh water on Earth rather than the mildly acidic water inferred from Opportunity's earlier discoveries at Eagle, Endurance, and Victoria craters.

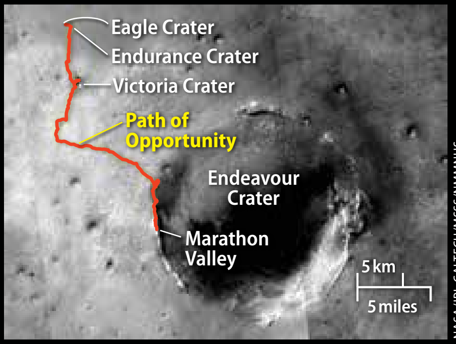
Even though Curiosity is the new kid on the block, having landed in August 2012, it surpassed its 1,000th sol in late May 2015. The sophisticated rover is now exploring the lower slopes of Mount Sharp, the looming 3-mile-high (5km) mountain of layered sedimentary rocks inside Gale Crater that drew the rover team to this landing site. Mount Sharp's layers record important parts of Mars' early warmer and wetter history. Curiosity's mission is to decipher that record in detail, layer by layer if need be, to learn as much as possible about the Red Planet's potential past habitability.

Like its predecessors, Opportunity and Spirit (which ceased transmissions in March 2010), Curiosity has found and continues to find ample evidence that both surface and groundwater once flowed on Mars. Recently revealed signs of that water include swarms of mineral-rich veins created when moving groundwater deposited materials that filled fractures in rocks. Other fresh discoveries of ancient water involve the detection of the iron-oxide mineral hematite,

NASA's Curiosity rover poses for a selfie on Mount Sharp in January 2015. This vista combines dozens of images captured by a camera that sits at the end of the rover's robotic arm. (Ground controllers positioned the arm so it would be out of the mosaic's frames.) The rim of Gale Crater appears at the top right of this image, and the peak of Mount Sharp is at the top left. NASA/JPL-CALTECH/MSSS



NASA's Opportunity rover captured this panorama from the rim of Endeavour Crater in January 2015. The clay materials Opportunity has found at Endeavour imply that groundwater once existed in this area. NASA/JPL-CALTECH/CORNELL UNIVERSITY/ARIZONA STATE UNIVERSITY

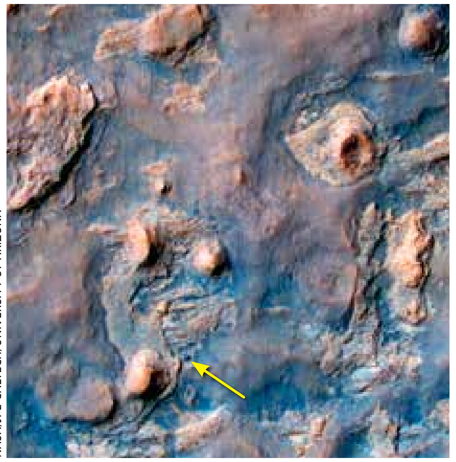


NASA/JPL-CALTECH/MSSS/NMMNHS; ASTRONOMY: KELLIE JAEGER

On March 24, 2015, Opportunity completed its first marathon when it passed the 26.219-mile (42.195 kilometers) mark on Mars' surface. The journey took more than 11 years and carried the rover from its landing site in Eagle Crater to the rim of Endeavour Crater.

Curiosity continues to explore the layered rocks on Mount Sharp's lower slopes. In September 2014, the rover drilled its first hole on the mountain to collect samples for onboard analysis. The hole measures 0.63 inch (1.6 centimeters) across and 2.6 inches (6.7cm) deep. NASA/JPL-CALTECH/MSSS

Curiosity discovered these two-toned mineral veins on the lower slopes of Mount Sharp in March 2015. They apparently formed when water flowed through fractured rock and deposited minerals in the cracks. The veins appear as a network of ridges, each of which measures up to 2.5 inches (6 centimeters) thick and half that in width. NASA/JPL-CALTECH/MSSS



NASA/JPL-CALTECH/UNIVERSITY OF ARIZONA

The Mars Reconnaissance Orbiter captured Curiosity and its tracks as it trekked through layered deposits in April 2014. The rover (arrow) appears blue in this image's exaggerated color.

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formed when water alters basaltic volcanic rock, and jarosite, an iron- and sulfur-bearing mineral that can arise when volcanic rock interacts with mildly acidic water.

These kinds of mineral discoveries coupled with spectacular images of finely layered sandstones and mudstones (fine-grained sedimentary rocks that typically form in water's presence) are beginning to paint a clearer picture of Mount Sharp. Scientists now suspect it is an enormous accumulation of sediments deposited in an ancient lake that periodically filled Gale Crater early in the planet's warmer and wetter history. It's an exciting hypothesis, but Curiosity needs to do a lot more climbing and sampling of additional layers to fully test it and tease out more details of the habitability of that possible ancient lake.

Curiosity's measurements of the martian atmosphere have been no less thrilling. A detailed search for methane early in the mission came up essentially blank, but in late 2013 the rover observed a tenfold spike in the abundance of this gas followed by a quick return to near-zero levels. Are there localized sources of this simple organic compound on Mars, perhaps a byproduct of geological processes such as a reaction between water and subsurface rock? Or could it be from some subsurface biological process? Although the latter seems unlikely, mission scientists don't want to discount any possibilities until they perform additional measurements and analyses.

The view from above

In the meantime, five active probes — three from NASA, one from the European Space Agency (ESA), and one from the Indian Space Research Organization (ISRO) — are plying the orbital seas above Mars. Using a variety of sophisticated instruments, these spacecraft are scouting the planet's geology, mineralogy, and atmospheric composition as well as searching for landing sites for future rovers and surface probes.

The most venerable of this quintet, and indeed the longest-operating spacecraft ever to explore the Red Planet, is NASA's Mars Odyssey. Since arriving in polar orbit in 2001, Mars Odyssey has circled the world nearly 60,000 times. In the process, it has discovered water ice in the south polar cap, found evidence that melting snow carved some geologically recent gullies, and helped find landing sites for Spirit and Opportunity.

It also has built up an impressive collection of chemical and mineral maps of the surface that have helped scientists understand the distribution of ground ice as well as new details about the planet's geology and mineralogy. Thanks to the mission's longevity, the Mars Odyssey team recently was able to complete a global set of infrared geologic maps at a resolution of around 330 feet (100 meters) per pixel. These are the highest-resolution maps of surface properties yet created for Mars and are helping researchers differentiate bedrock from sediments and dust-covered surfaces.

The second-oldest orbiter is ESA's Mars Express, which went into an elliptical orbit around the planet in late 2003. The spacecraft's instruments have been mapping the geology (in 3-D), mineralogy, and atmospheric chemistry of Mars during each close pass ever since. They have discovered minerals that can form only in the presence of water, vast amounts of water ice beneath the martian surface, and lava flows that might be only a few million years old. The High Resolution Stereo Camera continues to crank out spectacular topographic maps of volcanoes, craters, and canyons across the planet. The 3-D images are helping scientists understand the details of past geologic processes and adding key information to the search for future landing sites.

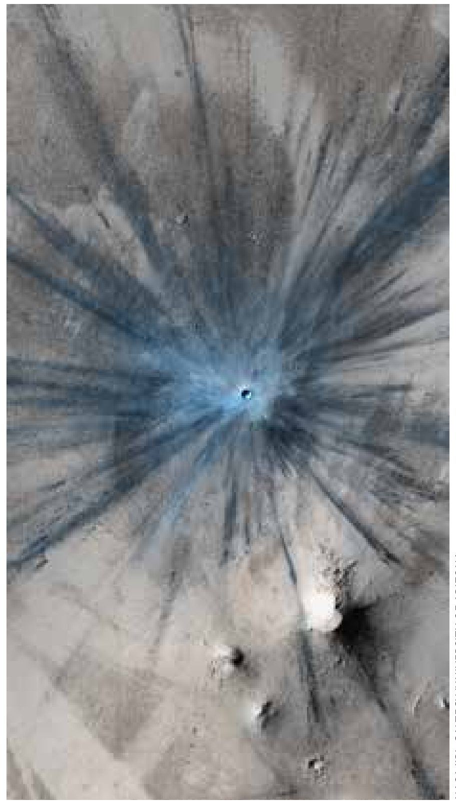
The Mars Reconnaissance Orbiter (MRO) ranks as NASA's most prolific Mars orbiter yet. Since it arrived in its circular polar orbit in 2006, the spacecraft has returned more than 30 terabytes of data — more than all other Mars missions combined. MRO captures the sharpest details from orbit and has helped planetary scientists map Mars' mineralogy and subsurface structure. The probe has found buried glaciers and the clay-rich minerals that led Curiosity's science team to Gale Crater.

The mission's Context Camera has imaged more than 90 percent of the martian surface at a resolution of about 20 feet (6m) per pixel. An even higher-resolution camera, the High Resolution Imaging Science Experiment, helps scientists study intricate details in small gullies apparently created by seeping water, identify fresh impact craters formed within the past decade, and even spot alien spacecraft parts on the surface — most recently, the likely wreckage from the 2003 crash of ESA's Beagle-2 lander.

The new arrivals

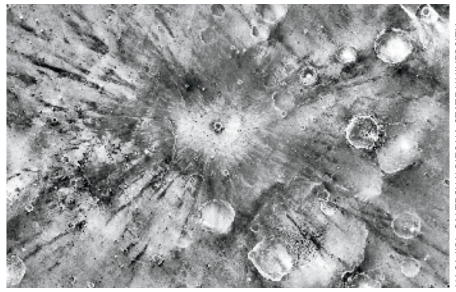
Two rookies recently joined these three veteran orbiters. ISRO's Mars Orbiter Mission (MOM), also called Mangalyaan, is India's first interplanetary mission. And when it entered Mars orbit in September 2014, that nation became the first to achieve success at the Red Planet on its first try. MOM's primary purpose is to test basic spacecraft and instrument capabilities as well as ISRO's ability to journey to Mars and operate successfully from orbit there. But in the process of demonstrating these technologies and skills, the spacecraft has captured some stunning color photos of the martian surface and atmosphere from its highly elliptical orbit.

NASA's newest artificial martian satellite arrived two days before MOM. The space agency designed the Mars Atmosphere and Volatile EvolutioN (MAVEN) orbiter specifically to study the Red Planet's atmosphere and especially the way it interacts with the stream of high-energy particles emitted by the Sun known as the solar wind. One of the mission's main goals is to test the hypothesis that the solar wind slowly eroded ancient Mars' thicker and warmer atmosphere, perhaps after the planet's core solidified and its early magnetic field disappeared. Mars once had a



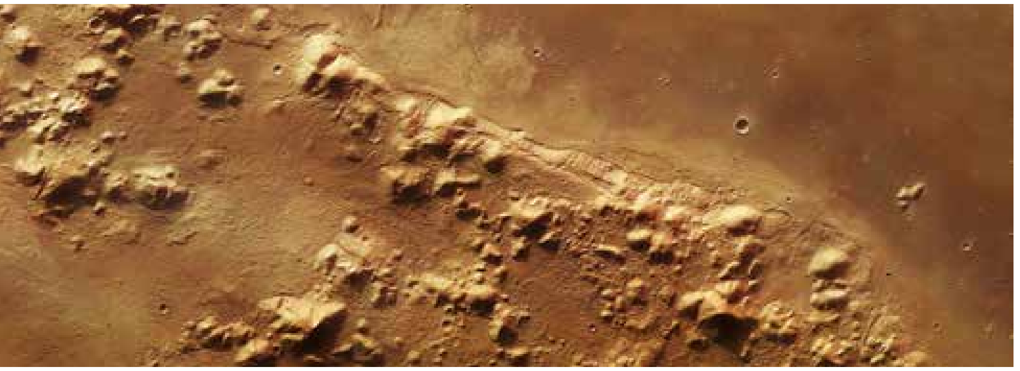
NASA/JPL-CALTECH/UNIVERSITY OF ARIZONA

NASA's Mars Reconnaissance Orbiter captured this impact crater, which formed in the past five years. This enhanced-color close-up reveals the 100-foot-wide (30 meters) scar and debris that spreads up to 9 miles (15 kilometers) away.



NASA/JPL-CALTECH/ARIZONA STATE UNIVERSITY

Scientists working with Mars Odyssey data recently created the highest-resolution global map of martian surface properties, in which warm areas appear bright and cool regions dark. This tiny section highlights the 4.3-mile-wide (6.9 kilometers) impact crater Gratteri.



The European Space Agency's Mars Express satellite captured this complex region of isolated hills and ridges in the southernmost section of Phlegra Montes in the planet's northern hemisphere. The probe's High Resolution Stereo Camera snapped this scene in October 2014 at a resolution of about 50 feet (15 meters) per pixel. ESA/DLR/FU BERLIN

strong magnetic field, a discovery made by NASA's earlier Mars Global Surveyor mission, but no longer does. Will MAVEN find that this is why Mars evolved into the cold, dry world it is today?

Early science results from MAVEN include the surprising discoveries of an auroral glow lower in the atmosphere than scientists expected and a dust layer much higher in the atmosphere than expected. Some researchers have suggested that the absence of a shielding magnetic field could allow the solar wind to penetrate deeper before it initiates the aurora. The origin of the high-altitude dust remains a mystery, however. Is it dust from Mars lofted upward by strong atmospheric currents? Or could it be dust raining down from the martian moons, Phobos or Deimos, or from streams of cometary dust? Scientists plan to test these and other hypotheses with additional MAVEN observations perhaps augmented by other orbiters.

Comet encounter

MAVEN and the other active spacecraft had front-row seats to one of 2014's most exciting astronomical events — October's close encounter between Mars and Comet Siding Spring (C/2013 A1). Although the comet's icy nucleus would miss the planet by approximately 87,000 miles (140,000km), astronomers predicted that its extended envelope would pass right over Mars and intermingle with its atmosphere.

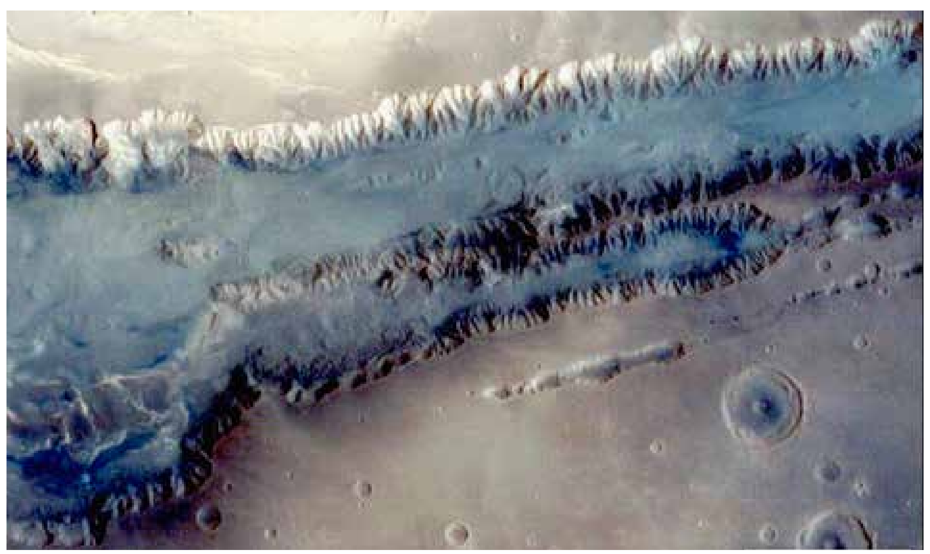
Cometary impacts and near-misses happen rarely, but they can teach us a lot about planetary atmospheres and comets themselves. Scientists remember vividly when Comet Shoemaker-Levy 9 collided with Jupiter in 1994, a dramatic celestial fireworks show that provided new information about the giant planet's cloud layers as well as the nature of high-speed impacts. Indeed, researchers studying the February 2013 meteor explosion over Chelyabinsk, Russia, analyzed the event using computer models developed partially from the Shoemaker-Levy 9 impact. Would Siding Spring deliver a similar show, or a show at all? No one was sure how the comet, which originated in the distant Oort Cloud, would behave.

MAVEN had perhaps the best view, and its science team commanded the spacecraft to observe the comet both before and after its Mars encounter. Although the probe's highly sensitive ultraviolet instruments are optimized to study the planet's upper atmosphere and aurorae, scientists often use these same kinds of tools to study comets.

There was some danger in making these observations, however. High-speed impacts by even tiny chunks of ice or dust ejected by the comet could cause a catastrophic failure of spacecraft components. To minimize the risk, mission managers manipulated MAVEN's orbit to "hide" the spacecraft behind Mars during the comet's closest approach. Better safe than sorry, especially since MAVEN had arrived at Mars just a month earlier. As the comet swooped past the Red Planet, controllers of the other Mars orbiters similarly protected their probes.

The spacecraft delivered a treasure-trove of information about Siding Spring. MAVEN, MRO, and Mars Express all detected strong increases in the number of electrically charged atoms in Mars' upper atmosphere. These ions formed as the comet's dust and gas slammed into the planet, stripping the atoms of electrons. MAVEN's ultraviolet instruments captured the bright glow from the comet's magnesium and iron ions, for example, and then the probe sampled these and other ions as it circled back around the planet. These observations were the first direct measurements scientists had ever made of ionized material from an Oort Cloud comet in a planetary atmosphere.

Comet Siding Spring also must have produced an impressive meteor shower. Unfortunately, the cameras on Opportunity and Curiosity were built to image the daytime surface and not the nighttime sky. Their relatively short exposures didn't capture any meteors and rendered the comet as little more than a fuzzy blob.



Although India designed its Mars Orbiter Mission only to demonstrate technology, the spacecraft has returned some stunning images since arriving in September 2014. This one shows part of Valles Marineris, a canyon system that spans 2,500 miles (4,000 kilometers) and digs 4.5 miles (7km) deep. ISRO

Future exploration

Six national space agencies have now launched more than 40 missions to Mars since the first attempt in 1960. Only about half of these proved even partially successful, attesting to the difficulty in exploring the Red Planet. Despite the challenges, however, humans continue to send robotic emissaries and even have started thinking about plans for the first crewed missions, perhaps as soon as the 2030s.

NASA's Mars Atmosphere and Volatile Evolution spacecraft discovered a martian aurora three months after it arrived in September 2014. This artist's concept shows the probe's ultraviolet imager capturing the glow. NASA/UNIVERSITY OF COLORADO

The martian armada targeted Comet Siding Spring (C/2013 A1) in October 2014. In this artist's concept, NASA's three orbiters watch as comet material crashes into the atmosphere and ionizes atoms from the deep-space visitor. NASA/JPL-CALTECH

The dark reddish lines angling to the upper left in this Mars Reconnaissance Orbiter image are active flows extending downhill from Hale Crater's central peaks. Scientists think the flows might be caused by seeping water. NASA/JPL-CALTECH/UNIVERSITY OF ARIZONA

Indeed, several missions in the works have direct connections to the eventual human exploration of Mars. In 2016, NASA will launch Insight, a lander based on the successful design of the 2008 Phoenix spacecraft. Insight will deploy a sensitive seismometer and heat-flow probe to search for signs of seismic or geothermal activity. Is Mars geologically dead or still active? Insight is designed to find out during its two-year primary mission, which will start in late 2016.

Also in late 2016, ESA, in cooperation with the Russian space agency, Roscosmos, will deploy the ExoMars Trace Gas Orbiter. This spacecraft will study methane and other minor atmospheric gases that might provide clues to the planet's geologic and possible biologic evolution. As part of the mission, the orbiter will deploy an entry, descent, and landing demonstration module called Schiaparelli. ESA expects Schiaparelli to prove the agency's ability to make a controlled landing on Mars' surface. If it survives touchdown, the spacecraft will conduct a science mission lasting two to eight sols designed to study the landing site's atmospheric conditions.

ESA will attempt its first Mars rover, once again in cooperation with Roscosmos, with ExoMars. Currently scheduled for a 2018 launch, the rover will use cameras, spectrometers (which analyze elemental composition), radar, and a drill to study the geological history of a past watery environment on Mars.

Understanding the detailed nature of the martian environment is also at the forefront of NASA's plans for its next Mars rover, tentatively called Mars 2020 after the year of its planned launch. To save money, some 80 to 90 percent of the rover will be constructed from spare parts from Curiosity. NASA envisions Mars 2020 as a first step in a longer-term set of missions designed to bring samples back from Mars. The rover will feature high-resolution cameras, spectrometers, and drilling/coring systems that will allow it to physically sample a variety of surface materials and cache them for potential transport to Earth on future missions.

Many planetary scientists believe that the next major leap in Mars exploration, and a critical step toward eventual human exploration of the Red Planet, will be to bring these carefully selected samples of soils and rocks to Earth for detailed geochemical and biological analysis. Are there chemical compounds in the soils that could degrade space-suit seals or other systems needed for life support? Is martian dust toxic to the human respiratory system in some unanticipated way? Can explorers extract resources such as oxygen and water from common Mars surface materials?

The future of Mars exploration looks as promising as the present. Future rovers may employ a small helicopter to scout ahead, finding features of interest and allowing ground controllers to plot the best driving routes. NASA/JPL-CALTECH

A primary goal of the Mars 2020 mission is to collect samples that can begin to answer such questions. Engineers are currently working on ways to cache these samples and decide the best way to return them to our planet.

I believe the human fascination with Mars stems in part from the fact that the deeper we look at it, the more we see parallels with our own world's past. Early in its history, Mars was much more Earth-like than it is today. It was warmer and wetter — at least in places. Heat from the Sun, geothermal sources, and impacts provided abundant energy, and the rain of asteroid and comet impacts that pelted Mars and the rest of the planets provided a steady supply of organic molecules.

Water, energy, and organic molecules are the key ingredients needed for life as we know it. Past and present missions have helped us discover that Mars was indeed a habitable world long ago. Upcoming missions, including the first human explorers in the not-too-distant future, will be working to up the ante, trying to find out if Mars was — or still is — not just habitable, but inhabited.

◄ **During Curiosity's 177th day on the Red Planet — February 3, 2013 — it took the dozens of images that, combined, make this full self-portrait. Soon after, the rover drilled into its first rock, becoming the first machine to sample the interior of another planet.** NASA/JPL-CALTECH/MSSS

Curiosity's latest findings from Mars

In August 2012, NASA's newest rover landed in Mars' Gale Crater. From finding ancient streambeds to analyzing hundreds of samples, the rover has kept busy helping scientists learn about the Red Planet's habitability. **by Sarah Scoles**

More people tuned in to see the Curiosity rover land on Mars than watch CNN during Sunday prime time. When NASA's most sophisticated, mobile, and outfitted robot touched down August 6, 2012, half a million viewers sat on the edges of their seats. A sky crane lowered Curiosity to a soft arrival on a planet it had traveled 352 million miles (567 million kilometers) to study. In the months since, the rover and the scientists who control it have been working hard to determine what Mars is like now, what it was like in the past, and what its past and present might mean for the past, present, and future of Earth.

A wild descent

Curiosity touched down in Gale Crater, a depression 96 miles (154km) across, near an alluvial fan that is called Peace Vallis — a cone-shaped buildup of debris from, presumably, once-flowing water.

"We didn't just stumble into this area," said John Grotzinger, Curiosity's project scientist, in a press conference March 7, 2013. Scientists chose Gale Crater after much debate about balancing safety and science. After all, it doesn't matter if interesting geology lies at the top of a boulder-strewn outcrop if your rover drives off a cliff. Gale Crater presented few such physical obstacles and appeared to offer diverse geology within a small area. Proximity is important: While the rover can move, engineers expect it to drive only 12 miles (20km) in its lifetime, making targets separated by 15 miles (24km) undesirable.

Gale Crater is also home to Mount Sharp, a 18,000-foot-tall (5.5km) mountain toward which Curiosity currently is traveling. But it's going to take a while to get there. Sharp is 5 miles (8km) from the rover's landing site, and Curiosity's longest day of driving has thus far been 464 feet (142 meters). The mound will be worth the wait, though, according to scientists. "Orbiting spacecraft suggest that the lower layers of this mound contain minerals formed in the presence of ancient water," says Nadine Barlow, a Mars expert and professor at Northern Arizona University in Flagstaff, "while the upper layers appear drier and may contain evidence of more recent, but still distant, volcanic activity."

The mound will surely prove to be a gold mine. After spending 11 months investigating Gale's depths, Curiosity set out for Mount Sharp on July 4.

But what, exactly, did researchers hope to learn when they set metal feet on this planet? Which questions has the rover answered already, and which new questions has it brought up? As Grotzinger said at the March press conference, "When you land on Mars, strange things can happen." While some of Curiosity's discoveries have not been surprising, others have changed the public conception of Mars from a dead, dusty place to one that has been evolving for billions of years and continues, even now, to do so.

When NASA launched Curiosity, it had biological, geological, and chemical goals. But the mission's umbrella objective is to determine whether Mars was ever habitable. Grotzinger was quick to point out, though, that the rover is not there to determine whether metabolizing microbes actually were on Mars. "We are not a life-detection mission," he said in March. Curiosity instead will determine whether life could have arisen and survived there. And the answer is directly applicable to us mammals and microbes: If Curiosity discovers that Mars used to be hospitable and has turned barren, what does that mean for our planet?

Christopher Edwards, a postdoctoral fellow at the California Institute of Technology and a member of the Curiosity science team, confirms, "[We're] going to look for what happened on Mars, how that happened differently on Earth, and how that allowed life on Earth to thrive."

Red biology

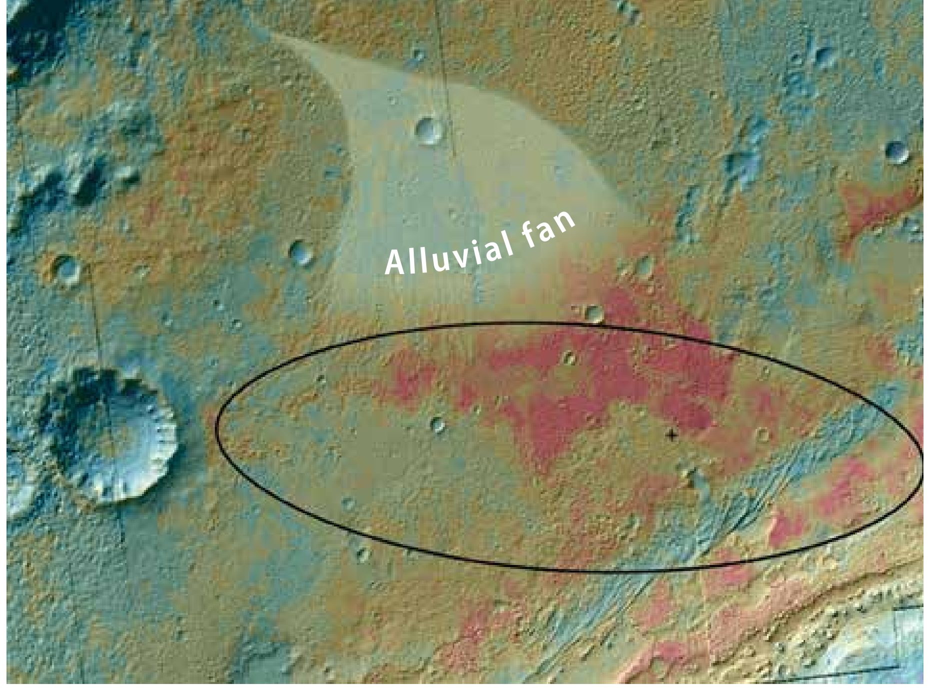
Curiosity has been busy helping scientists piece the planet's timeline together. During the rover's first year at work, it collected 190 gigabits of data; took more than 36,700 full images and 35,000 thumbnail images; fired lasers at targets more than 75,000 times; fully characterized rock samples; and drove more than 1 mile (1.6km).

The data are yielding serious results. The first came March 7, when NASA announced that Curiosity had discovered a streambed in which life could have survived.

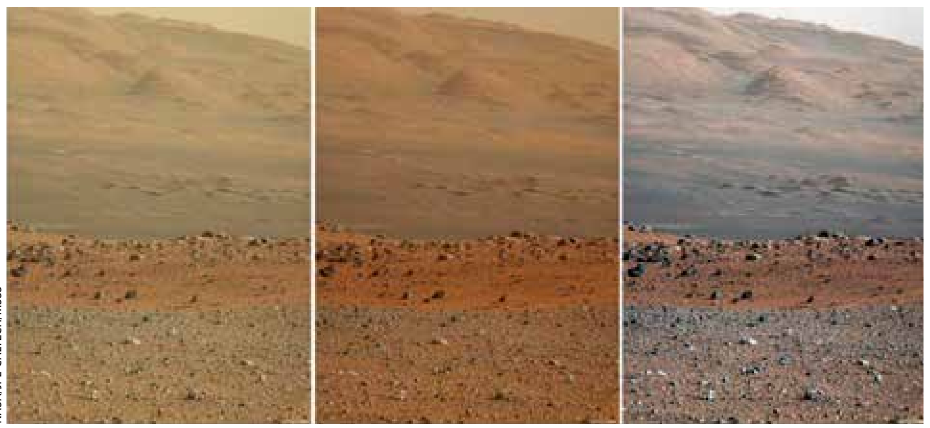
"We have found a habitable environment that is so benign and supportive of life," Grotzinger said at the time, "that, probably, if this water was around and you had been there, you would have been able to drink it."

The location, Yellowknife Bay, was not just wet — it had Goldilocks conditions: salty but not too salty, not too acidic, not too basic, and full of porridge-like chemical energy for metabolism. These results came from the first rock Curiosity drilled, February 8. The fine-grained rock, called John Klein, sits where streams appear to have descended from the crater's rim, perhaps leaving standing water, and is covered in nodules and veins. The rover bored a 2.5-inch (6.4 centimeters) hole into it, sending samples to its Sample Analysis at Mars (SAM) and Chemistry and Mineralogy (CheMin) instruments, which investigate chemical makeup.

A month passed before NASA announced that the sample suggested a water-wet, life-friendly spot. When Curiosity ran John Klein through its spectrometers and X-ray diffractors, the agency said, it found sulfur, nitrogen, hydrogen, oxygen, phosphorus, and carbon. Sulfates (sulfur plus oxygen) signal the presence of water. Ancient, hardy bacteria on Earth use sulfides (compounds containing sulfur minus two electrons) as fuel. DNA, meanwhile, is



This map shows Gale Crater, where Curiosity touched down in August 2012. The colors represent the terrain's ability to hold heat. Red loses thermal radiation slowly, suggesting the material in the soil is cemented tightly together. The topography, including a fan-shaped deposit of debris called Peace Vallis, suggests water once flowed through this area on Mars. Curiosity, which landed inside the black ellipse, has seen rounded pebbles cemented to rocks, material that may have been carried and polished by a moving river. NASA/JPL-CALTECH/UNIV. OF ARIZONA



NASA/JPL-CALTECH/MSSS

Scientists receive images directly from Curiosity — the raw files (left) — but from there, they have two options. They can process the pictures to show the view as it would look if you were standing on Mars (middle), or they can white-balance the photos so the scene looks as it would under Earth-lighting (right).

Two different Mars rovers — Opportunity and Curiosity — have seen concretions (the small spheres pictured here) and cemented rocks, geological features that form in the presence of water. Opportunity's Wompay rock (top) appears to have formed in an acidic, inhospitable environment. Curiosity's Sheepbed rock, however, formed in a neutral, non-salty environment with plenty of chemical energy. NASA/JPL-CALTECH/CORNELL/MSSS

made of phosphates (phosphorus plus oxygen), carbohydrates (carbon, hydrogen, and oxygen), and nitrogen groups. In short, John Klein contains the ingredients necessary to whip up a batch of life. And the pH-balanced, fresh(ish) conditions would have been favorable to that life's survival.

"A fundamental question for this mission is whether Mars could have supported a habitable environment," says Michael Meyer, the lead astronomer for NASA's Mars Exploration Program located in Washington, D.C. "From what we know now, the answer is yes." Mission accomplished, but far from over.

Sarah Scoles *is an associate editor at* Astronomy *magazine.*

Water, water

So now we know Mars was, at some point, wet. But how long was the water there? How deep and extensive was it? Initial results from a third Curiosity instrument — the Mast Camera (MastCam), which uses near-infrared vision to detect iron- and water-bearing minerals — suggest the planet's wet habitability was not limited to the resting place of a single rock but extended at least up to Mount Sharp.

Scientists have long had solid evidence that water used to flow across the surface of the Red Planet. Data dating back to the 1970s provided proof of the H_2O molecule's existence, but Curiosity is doing its part to show that the H_2O came in the form of rivers, streams, and lakes. In addition to drilling rocks toward that end, the rover also has scooped soil. At a sandbox called Rocknest, its SAM instrument heated the dirt to 932° Fahrenheit (500° Celsius), and evidence of water, sulfur, and chlorine compounds popped out.

But the most satisfying answer came from close-up pictures the MastCam took of three rocks. The images are from the first 40 days of the mission, but analysis did not come right away. In June, scientists determined that "Goulburn," "Link," and "Hottah" — as the rocks are affectionately known — are glued-together pebbles. On Earth — and so, presumably, on Mars — sediments stick together like this when they are immersed in flowing water. To create deposits the size of Goulburn's, Link's, and Hottah's, the martian stream would have been ankle- to hip-deep and flowing about 3 feet per second (1 m/s).

Although scientists speak of the streams in the past tense, Mars retains some of its water in frozen form. Curiosity found out just how much is there, searching for ice on-the-go as it traveled from Yellowknife Bay to its next big landmark: a three-terrain intersection called Glenelg. Its Dynamic Albedo of Neutrons (DAN) detector searched for slow neutrons, which indicate the presence of water. Cosmic rays constantly strike the planet's surface, kicking neutrons out of their atoms. If the ejected neutrons interact with hydrogen atoms on their way out of the ground, they slow down. DAN looks for low-energy neutrons and, based on their abundance, can tell how full of water molecules the ground is. On its travels, Curiosity sometimes saw water merely on the surface, but other times the chemistry extended more than 15 inches (40cm) underground, making up between 1.3 and 3 percent of the total material.

Remarkable Mars

As temperatures on Mars changed, it was unable to hold on to its liquid water. Its water-friendly warmth was due solely to its atmosphere, which is now an inhospitable 95.95 percent carbon dioxide and 0.146 percent oxygen, according to Curiosity's latest readings. Long ago, though, Mars' atmosphere was different. Its many giant volcanoes were active, and they now act as road maps. "Even though they might not be as exciting as life," says Joshua Bandfield, a Mars expert who was on the team that characterized Curiosity's landing site, "volcanoes can point you to both where the liquid water and energy sources were in the martian past." At one point in Mars' history, they also spewed plumes of methane, a powerful greenhouse gas, into the air. The gas trapped the Sun's heat, and the heat reradiated from the martian ground — a combination that potentially warmed Mars enough for liquid water to exist despite its distance from the Sun.

But Mars' atmosphere is depleted now, too thin to keep the planet warm, and Curiosity discovered how, exactly, the once-thick blanket became so threadbare. Its SAM instrument analyzed the abundances of isotopes, which are versions of the same element with different numbers of neutrons. The more neutrons an isotope has, the "heavier" it is. Scientists can compare the light-to-heavy isotope ratio in today's martian atmosphere to that of the early solar system. If Mars were not letting atoms escape, the two would be the same.

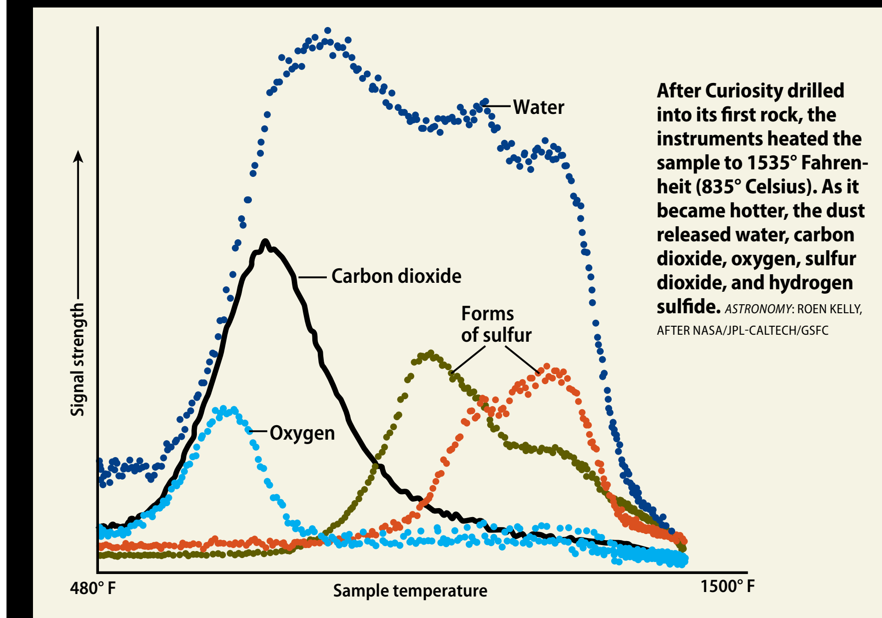
But SAM found that heavy isotopes of hydrogen, carbon, oxygen, and argon are more prevalent on Mars than they were in the solar system's early years. In other words, the planet, which has low gravity and no significant magnetic field, can't hang on to its lighter isotopes. It has evolved since its early years, losing lighter atoms. It actively continues to lose its less substantive substances today. And the more scientists learn about the planet, the more they see it as a generally dynamic place, rather than a Pompeii-style preservation of a bygone era.

Mars' surface is lively, a fact Curiosity must contend with to reach its next destination. Simone Silvestro, a postdoctoral researcher at the SETI Institute in Mountain View, California, demonstrated that the martian wind is, as you read this sentence, reshaping the planet's dunes. He compared results from ground-level wind sensors to satellite images and saw that the wind pushed the dunes surrounding Mount Sharp some 1.3 feet (0.4m) each year. "The action of the wind is the most active process in shaping the planet," Silvestro says.

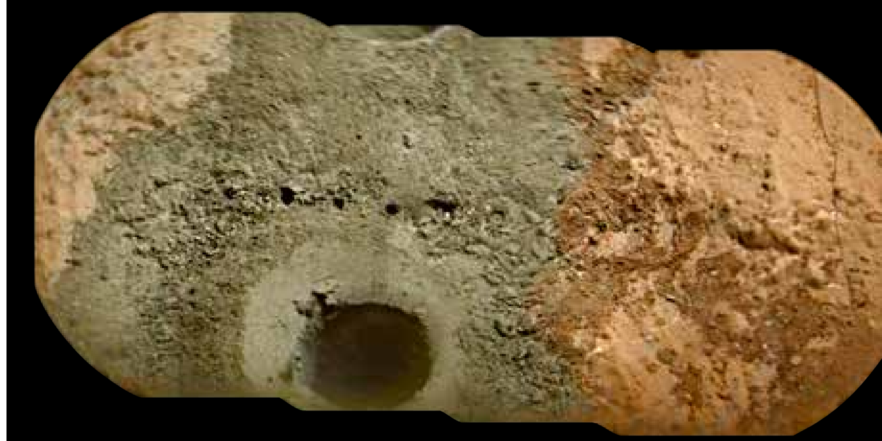
Silvestro works with research scientist Lori Fenton, who is excited by this proof that Mars isn't a "dead" planet. "You can

Curiosity's 1.6-inch-wide (4 centimeters) scoop created these divots in the sand at Rocknest. At this location, the sand consists of a crust of coarse grains atop finer dust. NASA/JPL-CALTECH/MSSS

Drilling into John Klein



After Curiosity drilled into its first rock, the instruments heated the sample to 1535° Fahrenheit (835° Celsius). As it became hotter, the dust released water, carbon dioxide, oxygen, sulfur dioxide, and hydrogen sulfide. *ASTRONOMY*: ROEN KELLY, AFTER NASA/JPL-CALTECH/GSFC



Curiosity collected the first drilled sample from another planet. The next day, its Chemistry Camera sent laser pulses into the rock, creating the smaller holes. The larger hole has a diameter of 0.6 inch (1.6 centimeters) and is 2.5 inches (6.4cm) deep. NASA/JPL-CALTECH/LANL/IRAP/CNES/LPGNANTES/IAS/CNRS/MSSS

At the Rocknest site in November 2012, Curiosity's Mast Camera took this panoramic mosaic. NASA/JPL-CALTECH/MSSS

actually see how wind and water have played a role in martian history," she says. "To me that's living, breathing." The rover will have to travel up and over this lively surface in the coming months to continue its scientific work.

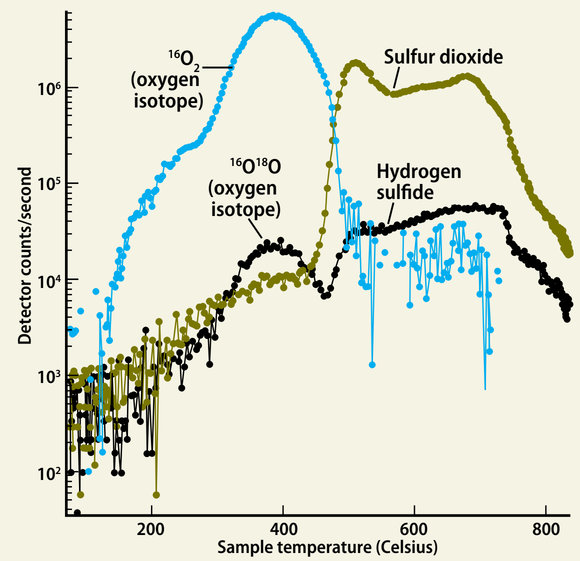
A time machine

Mars was more violent between 3.5 and 4.5 billion years ago. This time period, known as the Noachian Era, saw the formation of large impact craters, such as Gale, which are ready-to-use tools for scientists. Barlow phrases it more aggressively: "I like to refer to impact craters as 'nature's drills.'"

Because of their low-lying bottoms, crater floors collect material that flowed from higher elevations. If they were once wet, for instance, they retain sediments and deposits. Some rocks in Gale formed when flowing water cemented material together, while some rocks formed from volcanic activity. Curiosity can investigate both types.

Gale Crater showcases parts of Mars that are below the surface but used to *be* the surface. "The layers exposed in craters provide insights into past environments quite different from what we see on the planet today," says Barlow. If Curiosity looks at the different strata — just like a scientist in the Grand Canyon might sample different elevations along the rock walls — it can help scientists learn more about the planet's past.

What's inside martian sand?



The sand that Curiosity scooped at Rocknest contains sulfur, chlorine, and oxygen compounds. To determine the material's composition, the Sample Analysis at Mars instrument heated it and analyzed the resulting emissions. Perchlorates — compounds containing chlorine and oxygen — in the sample could indicate the presence of accompanying organic molecules. *ASTRONOMY*: ROEN KELLY, AFTER NASA/JPL-CALTECH/GSFC

NASA/JPL-CALTECH/MSSS

Curiosity's Mast Camera snapped this portrait of the rover's Alpha Particle X-Ray Spectrometer (APXS). Scientists directed the camera to take the image to determine whether APXS had been covered in dust during the rover's landing.

Mount Sharp, where the rover is headed, also has rocky strata compacted together like a book of pressed flowers, if a book of pressed flowers contained flora from geological eras separated by millions of years.

It's no Earth

While it's unlikely that Mars ever had mammals, it was habitable, at least in spots. But like on Earth, conditions there vary from region to region, just as Earth is home to both the Badlands and the bayou. For instance, Curiosity has found that the planet's relative humidity changes based on its location. The Rover Environmental Monitoring Station (REMS) saw the humidity drop from 60 percent to about 5 percent in the 0.25 mile (400m) between the landing site and the sandy area where the rover spent its 55th to 101st days on Mars.

The surface temperature, though, did not depend on the rover's location, at least not on small scales. The average daily high has been a still-freezing 32° F (0° C), while the low averages –94° F (–70° C). On Earth, the average temperature is a comfortable 61° F (16° C), while Mars is only a frigid –31° F (–35° C).

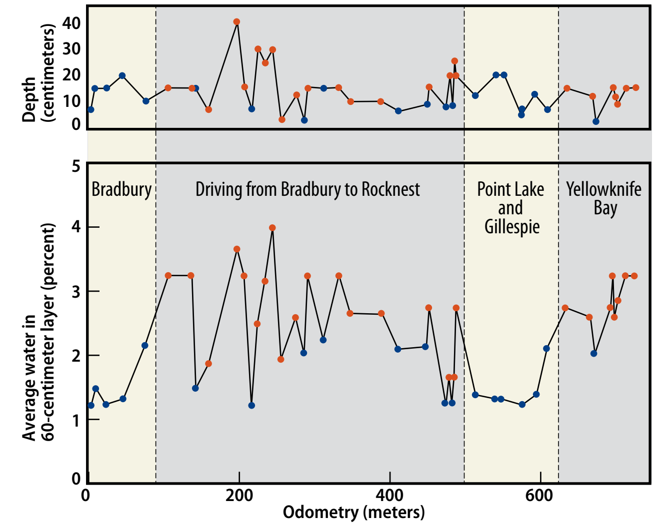
Curiosity, so mindful of its own condition that it is almost self-aware, also uses REMS to determine how strongly the atmosphere is pressing down. The pressure between mid-August 2012 and late February 2013 — about a quarter of a martian year — slid upward by 0.029 pound per square inch. This seasonal change occurs because the spring sunlight causes carbon dioxide (CO_2) to sublimate from the southern polar cap. The CO_2 becomes part of the planet's atmosphere, increasing its mass by 30 percent each time the season rolls around. But even the highest pressure is 0.0095 atmosphere, not even a hundredth the pressure we experience on Earth.

So although the planet resembles Utah, remember Earth and Mars are still quite different. For one, everything Curiosity sees is gigantic. "The scale of features on Mars is massive," says Edwards. "When I look at a crater, I always have to tell myself, 'That crater is bigger than the entire Los Angeles Basin.'" Secondly, everything Curiosity sees

NASA/JPL-CALTECH/MSSS AND PSI

Some martian geology is remarkably similar to that of Earth. The Link outcrop on Mars (top) has small gravel pieces called clasts embedded in the larger rock. Erosion can release clasts, which fall to the ground and create piles of pebbles. A similar sedimentary formation on Earth is on the bottom.

Surface water on Mars



Curiosity's Dynamic Albedo of Neutrons instrument detects the presence of hydrogen, and thus water. On Mars, most of this water is bound to minerals, which are then called "hydrated." The amount of water near the surface of Yellowknife Bay is an average of 3 percent of the total material. *ASTRONOMY*: ROEN KELLY, AFTER NASA/JPL-CALTECH/RUSSIAN SPACE RESEARCH INSTITUTE

is old. "Look at a typical rock in your backyard," Edwards continues. "It probably formed 100 million years ago. On Mars, rocks have been sitting on the surface for billions of years. You have an unadulterated record of rocks that often formed 3 billion years ago, a period that has been largely erased on Earth."

Sending a rover to Mars is like going back in time. When Curiosity samples a streambed, it peers into a period in the solar system's history that we — earthlings who build structures on top of our wetter, more volcanic, more pressurized, and more tectonic planet — cannot easily access.

Where to next?

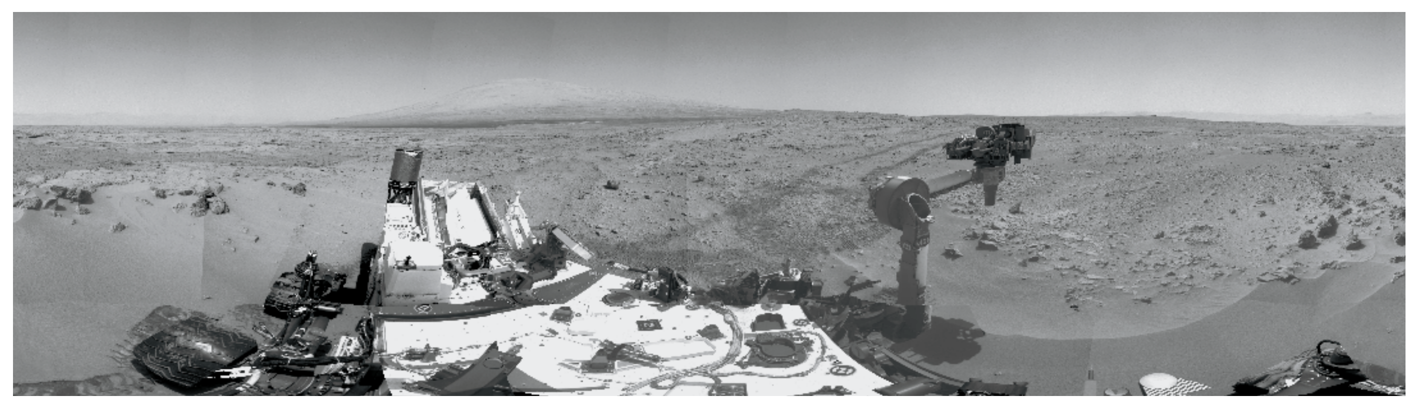
Curiosity is continuing its long trek toward Mount Sharp, and it will stop along the way whenever scientists see something interesting. So far, their plans have encountered only minor blips: Curiosity's computer had a memory glitch February 28; it flipped into "safe mode" after a software malfunction March 16; and the rover popped a wheelie for a while in June. But the system generally works. In fact, it works so well that Curiosity sometimes operates without a baby sitter, reacting to obstacles without checking in with ground control.

The rover's first year of results will help space agencies put astronauts' boots on the ground — eventually. Astronomers need to thoroughly understand this desert planet if the United States is going to send humans there in 2020, as President Obama plans. Curiosity is pushing that agenda forward by learning where meltwater-ice supplies are and measuring how much radiation reaches the surface each day. With current technology, the level of radiation — about a CT scan's worth every five days — is too high. But as long as scientists know that, they can work to innovate new protections.

Aside from the logistical investigations into whether humans can hack it on Mars, Curiosity is making inquiries into Earth's prehistory. In September, scientists announced that they had found a rock, which they called Jake Matijevic, that was nearly indistinguishable from a certain kind of volcanic rock on Earth. The similarities suggest Mars' interior may be more similar to Earth's than anyone thought.

"You can think of planets as giant laboratory experiments set up 4.5 billion years ago," says Bandfield. "Each has slightly different proportions of rock, water, etc." How did those slightly different proportions lead to such radically different results? Specifically, how did they produce Mars — a planet that may have been habitable, but not inhabited, in the distant past — and Earth, a geologically similar planet now teeming with everything from upright mammals to archaebacteria?

"We study these other planets to reflect on ourselves," says Edwards. "It's a system, right? Our solar system."



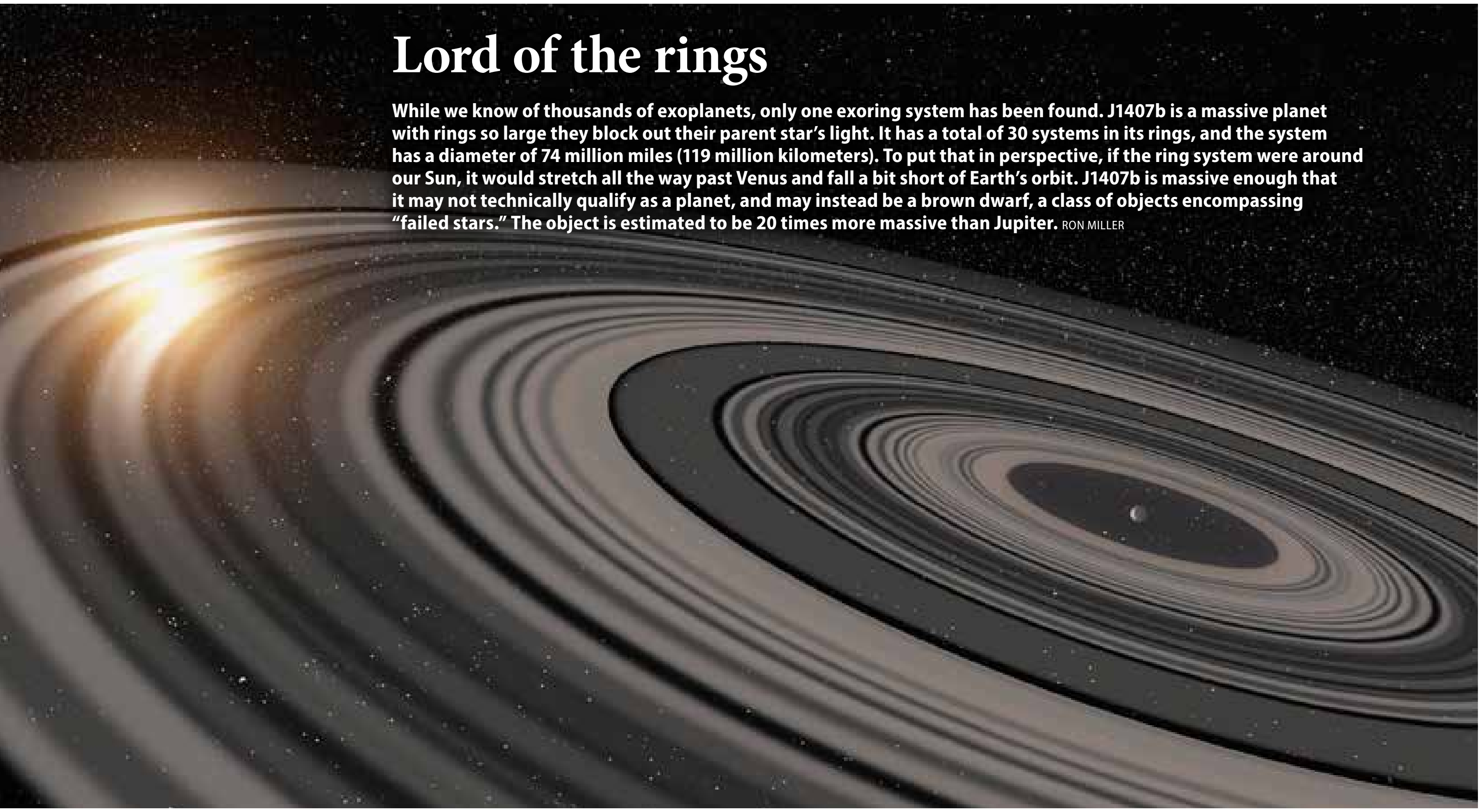
In this 360° image, taken during Curiosity's 59th Earth day on Mars, the Navigation Camera recorded Rocknest in the foreground and Aeolis Mons (Mount Sharp) in the background. The mountain rises some 18,000 feet (5.5 kilometers) from the floor of Gale Crater. The rover currently is on its way to Mount Sharp, leaving more tracks like those in the right portion of the image. NASA/JPL-CALTECH

How moon dust will put a ring around MARS

Phobos, a moon of Mars, is destined to be shredded, changing the Red Planet forever.

by Joel Davis

Someday, Mars' moon Phobos will slip past a certain point in its degrading orbit and get ripped apart by tidal forces, forming a ring. This illustration depicts Phobos midway through that process, overlooking the Red Planet. RON MILLER FOR *ASTRONOMY*



Lord of the rings

While we know of thousands of exoplanets, only one exoring system has been found. J1407b is a massive planet with rings so large they block out their parent star's light. It has a total of 30 systems in its rings, and the system has a diameter of 74 million miles (119 million kilometers). To put that in perspective, if the ring system were around our Sun, it would stretch all the way past Venus and fall a bit short of Earth's orbit. J1407b is massive enough that it may not technically qualify as a planet, and may instead be a brown dwarf, a class of objects encompassing "failed stars." The object is estimated to be 20 times more massive than Jupiter. RON MILLER

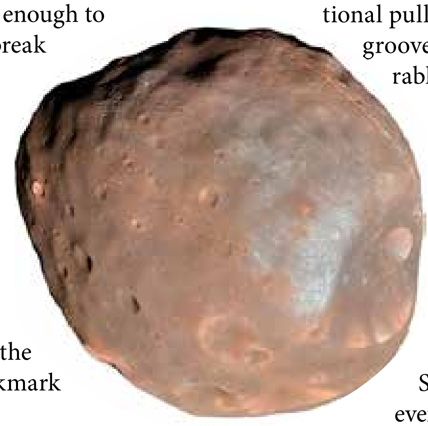
Phobos, it seems, is not long for this universe — at least on the large cosmic timescale.

Astronomers have long known that Phobos, the larger and nearer of the two martian moons, is slowly spiraling inward to eventual destruction. The end result won't be pretty: Phobos will slip closer and closer toward Mars, then strike a gravitational line where the planet's tidal forces will be strong enough to rip it apart. The rubble pile-like moon will break into smaller boulders, rocks, and dust, and will spread out in orbit around Mars.

Mars will join the gas giants in having a spectacular feature: a ring system.

It could be 25 million years from now. It could be up to 75 million years. Recent discoveries about the little moon's composition and density, however, make it far more likely that its death dive will happen sooner. The pieces that don't form a ring will fall to the surface, smashing with enough force to pockmark Mars with new craters.

"A lot of planetary science focuses on what happened in the past and what's happening now," says planetary scientist Benjamin A. Black. "It's not often that we look at the future, at what will happen." Black, a City University of New York professor, and graduate student Tushar Mittal from the University of California, Berkeley, have carried out a detailed examination of the eventual fate of Phobos.



NASA (PHOBOS)

It appears the process of coming apart at the seams has already begun. Images of Phobos taken by the Viking orbiters and other spacecraft show a network of grooves in the tiny moon's surface. At first they appeared to radiate from near Stickney Crater, and geologists assumed that the grooves were cracks caused by the ancient impact. Some certainly are just that, but not all. In 2015, Terry Hurford of NASA's Goddard Space Flight Center and his colleagues reported a new analysis of the grooves. Most of them actually radiate from the side of Phobos that constantly faces Mars; tidal forces caused by Mars' gravitational pull are deforming Phobos. Hurford believes the grooves are stretch marks, a visible sign of the inexorable grip of tidal forces on the moon.

The future martian ring will not be the only one in the solar system, of course. Nor will it be the only ring whose existence depends on a moon. There are rings across the giant planets: the four dusty rings of Jupiter; Uranus' 13 dark, thin rings; and Neptune's five faint rings and four enigmatic ring arcs are — like the future ring around Mars — all intimately linked to moons and moonlets. And of course, the most familiar ringed planet is Saturn, whose icy surrounding matter can be seen even through a small telescope.

Saturn's magnificent rings

Galileo Galilei saw what turned out to be Saturn's spectacular ring system in 1610. (He said the features looked like ears or handles.) But it wasn't until 1655 that Christiaan Huygens identified them as an entire system of icy rings. In 1856, famed physicist James Clerk Maxwell showed that the rings must be composed of a huge number of tiny particles (he called them "brick-bats"), each independently orbiting Saturn.

Since then, debate has raged over the origin, age, and composition of Saturn's rings. Are they leftovers from the formation of Saturn, or the remains of a shattered moon? As old as Saturn itself, or a relatively new addition? And why so much ice? Planetary scientist Robin M. Canup of the Southwest Research Institute in Boulder, Colorado, recently published a proposal that answers these questions. Canup suggests that Saturn's rings are the very ancient remains of a Titan-sized moon.

"Saturn originally had multiple massive moons like Jupiter," says Canup. These moons were large enough for their interiors to differentiate into layers of ices and a rocky core — less like a large comet and more like the four larger moons of Jupiter. When the large moons spiraled inward as Saturn finished its accretion, Canup says, the outer icy layers of at least one were stripped away. The core plunged into Saturn, and the icy remains eventually formed the planet's main rings. This, she says, explains why the particles making up the rings are 99.9 percent pure water ice. It also explains the striking difference between Jupiter's and Saturn's rings and satellites.

"The existence of Saturn's much more massive ring system is linked to Saturn having lost its large primordial inner moons," Canup explains. "Jupiter retained its large inner moons, [while] its dusty ring system is vastly less massive than the ring system at Saturn."

Creating a martian ring

Phobos isn't nearly the size of a planet, but many of the same mechanisms will drive its destruction. Its companion moon Deimos is about 7.8 miles (12.6 kilometers) in diameter and orbits Mars at an average distance of 14,580 miles (23,460km), far enough away to avoid Phobos' fate. Phobos is 13.8 miles (22.2km) in diameter. It circles the planet at an average distance of 5,827 miles

RINGS OF THE GIANT PLANETS

Jupiter's four faint and dusty rings probably formed by a different mechanism than Saturn's — and more recently — but its moons still play a vital role. Amalthea and Thebe are the likely sources of the material in Jupiter's outer two "gossamer" rings. Thebe orbits within the outer gossamer ring, while Amalthea lies near the outer edge of the inner gossamer ring. Metis and Adrastea, two other small moons, orbit near the outer edge of Jupiter's main ring, and are the sources of the dust grains making up the main and innermost halo rings.

Some forces work against the rings, keeping them relatively thin. Electromagnetic forces, a phenomenon called plasma drag, and even pressure from sunlight (called the Poynting-Robertson effect) continually remove the micron-sized particles from the rings. But particles sputtered off the moons by meteoroid impacts create dust and continually replenish the rings.

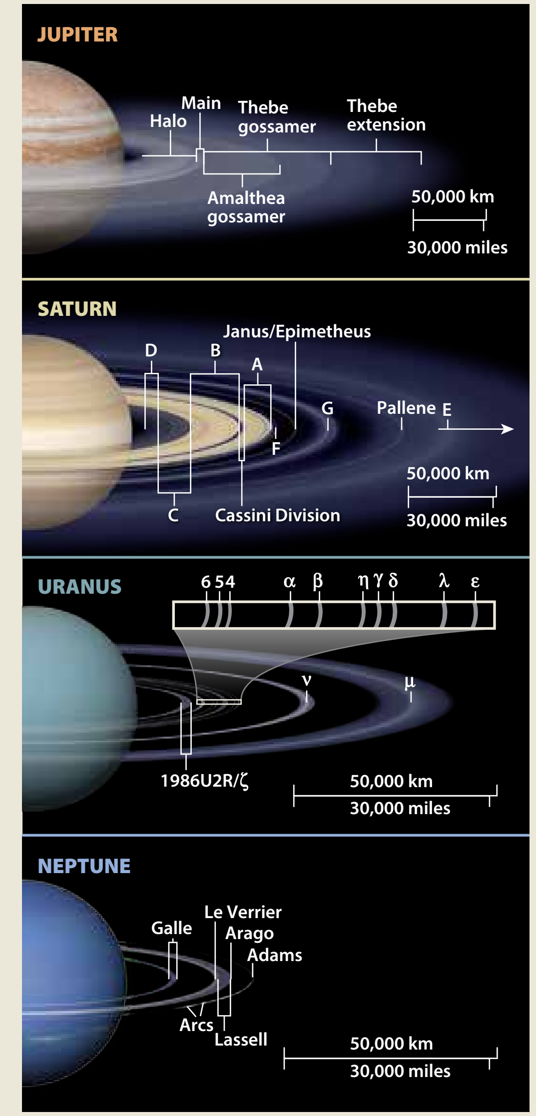
The 13 known rings of Uranus are unlike those of Jupiter or Saturn. All but the innermost and two outermost of the rings are quite narrow, ranging from just 0.6 to 59.6 miles (1 to 96 kilometers) wide. Their particles are larger than those in Jupiter's rings, but there's little dust. Instead, they're largely made up of ice with organic chemicals mixed in to give the dark appearances, unique among the outer solar system rings.

But there are similarities: Like Jupiter's and Saturn's rings, Uranus' rings are intimately associated with moons and moonlets. Primordial moons the size of Puck, 100 miles (162km) in diameter, or larger would have had a good chance of surviving for several billion years. But not all would escape a devastating fate. Computer simulations show that the 11 inner moons of Uranus are likely the remains of original larger moons broken up by cometary impacts. What's more, the current rate of meteoroid impacts among moons and other icy bodies at Uranus' distance is enough to create all the observed rings and dust bands circling that planet.

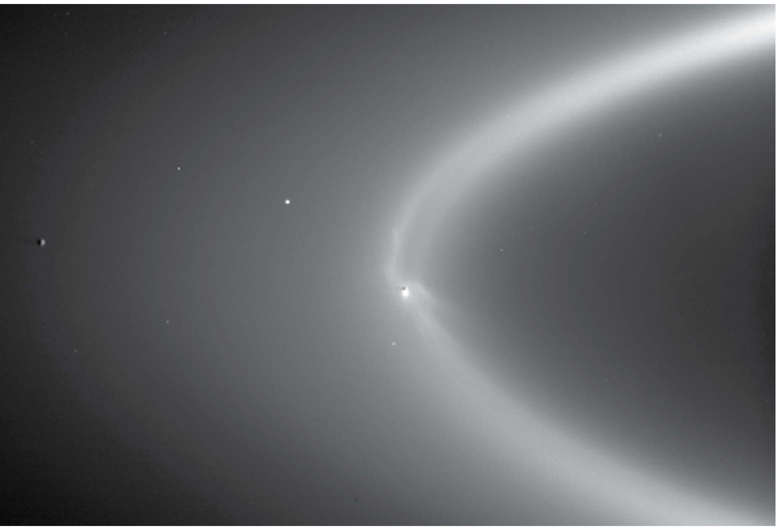
Because the rings appear to be young, probably not more than 600 million years old, the material in the rings must be continually renewed. Particles blasted off the tiny moons and still-unseen moonlets by collisions and meteoroid strikes continually add material to the rings, while the dust continues to dissipate.

Neptune's five rings and various dust bands are probably even younger than those of Uranus, and the same processes are likely responsible for them and the moons that orbit in or near them. Naiad and Thalassa orbit in the gap between the innermost Galle and Le Verrier rings, and Despina orbits just inside the Le Verrier ring. Galatea lies slightly inside the outermost Adams ring. These tiny moons are likely rubble-pile objects, agglomerations of fragments from earlier neptunian moons, weakly held together by gravity. The ring particles are material continually blasted off the moons by meteoroid impacts. Unlike the uranian rings, the rings of Neptune are quite dusty, thanks to the destruction of a satellite; at least 20 percent of the material is the size of smoke particles, and in some of the rings, that rises to 70 percent.

The Adams ring also has five distinct clumps or arcs of dust spanning about 40° in longitude. How they can exist for any length of time is a mystery, as these tenuous rings should have faded away. One explanation, by planetary ring expert Carolyn Porco, leader of the Cassini orbiter's imaging team, is that a resonance effect caused by Galatea's eccentric orbit may act to keep the particles in the arcs from spreading out and dissipating. — *J. D.*



All four giant planets — gas giants Jupiter and Saturn, and ice giants Uranus and Neptune — have ring systems. But each one is very different. *ASTRONOMY*: ROEN KELLY



▲The lines cutting across Phobos are caused by tidal stresses from the gravity of Mars slowly ripping its largest moon apart. NASA

◄The white object in the center of Saturn's diffuse E ring is Enceladus, a tiny moon with a liquid ocean. Geysers at the moon's south pole eject water into space, forming the ring. NASA/ESA

(9,377km). With an orbital period of just 7 hours, 39.2 minutes, Phobos is one of only 18 of the 181 known moons in the solar system whose orbital period is less than its planet's rotation period.

That's one of a few reasons why Phobos is doomed. "There are four factors in action," explains Mittal. "The tidal force of Mars; the centrifugal forces on Phobos, which is rotating; the gravity of Phobos; and the strength of Phobos. There's a balance among these. Tidal and rotational stresses act to pull Phobos apart; self-gravity and [tensile] strength act to hold Phobos together."

Just as our own Moon's gravity raises tides in both Earth's oceans and landmasses, Phobos creates a tiny tidal bulge in Mars. The bulge moves as the moon circles Mars, just as the Moon-caused tidal bulge moves around Earth. Because Phobos has an orbital period faster than the martian day, the tidal bulge lags behind Phobos and acts to gradually slow it in its orbit, sending Phobos slowly spiraling in toward the martian surface. The rate is about 0.79 inch (2 centimeters) per year. It's not much, but there is nothing to stop it.

"As Phobos gets closer to Mars," says Mittal, "the tidal stresses increase." The moon's self-gravity and tensile strength oppose the tidal forces, but eventually Phobos will drop to a distance — called the Roche limit — where the martian gravity will win the tug-of-war. Several studies confirm that Phobos' inward spiral will lead to its destruction in 25 million to 75 million years.

Phobos could stave off obliteration if it were a dense body, more able to resist the pull of gravity past the Roche limit. Unfortunately, data from the European Space Agency's Mars Express orbiter show that the moon has a density of just 1.9 grams per cubic centimeter. By comparison, our Moon has a density of 3.3g per cubic centimeter. Even tiny Themisto, Jupiter's smallest regular moon at just 4.9 miles (8km) in diameter, has an estimated density of about 2.6g per cubic centimeter. Mars Express also revealed that Phobos is porous, likely containing large voids, so it is probably a rubble pile, like many of Uranus' and Neptune's tiny moons.

In addition, Phobos' makeup is similar to carbonaceous chondrite meteorites like the ones that fell on Canada's Tagish Lake in 2000. These primitive meteorites are made of a bevy of loose, easily broken materials, including magnetite, olivine crystals, phyllosilicates, and complex organic molecules such as amino acids, and are about 10 percent water, formed in oxygen-rich regions of the early solar system. Phobos is not only a rubble pile with a weak gravitational field, but the rubble itself is somewhat frangible.

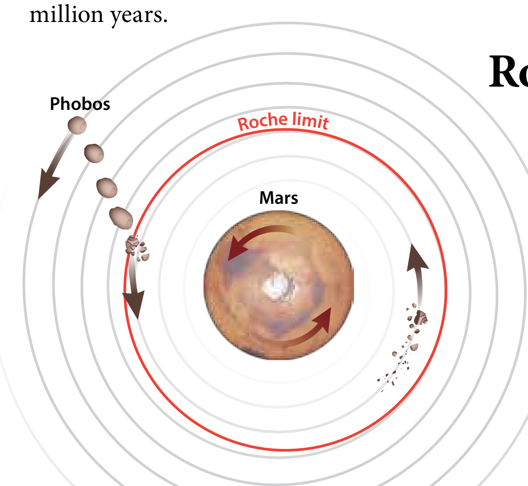
Then there's Stickney Crater, the giant impact basin on Phobos. Sometime in its past, Phobos was hit by an object that left a crater 5.6 miles (9km) wide — nearly half the moon's diameter. The impact surely fractured much of Phobos' interior, leaving it even weaker. From there, billions of years of meteoroid impacts have churned the surface of Phobos into a layer of fine dust about a hundred meters deep. Given the extremely weak surface gravity (escape velocity for Phobos is a mere 4.56 feet per second), the rock making up the rubble pile just barely stays put.

Black and Mittal used a numerical geotechnical model designed for large underground construction projects to estimate what they call the moon's "rock mass strength." The results place the finale for Phobos between 20 million and 40 million years from now, and give more details on its violent end.

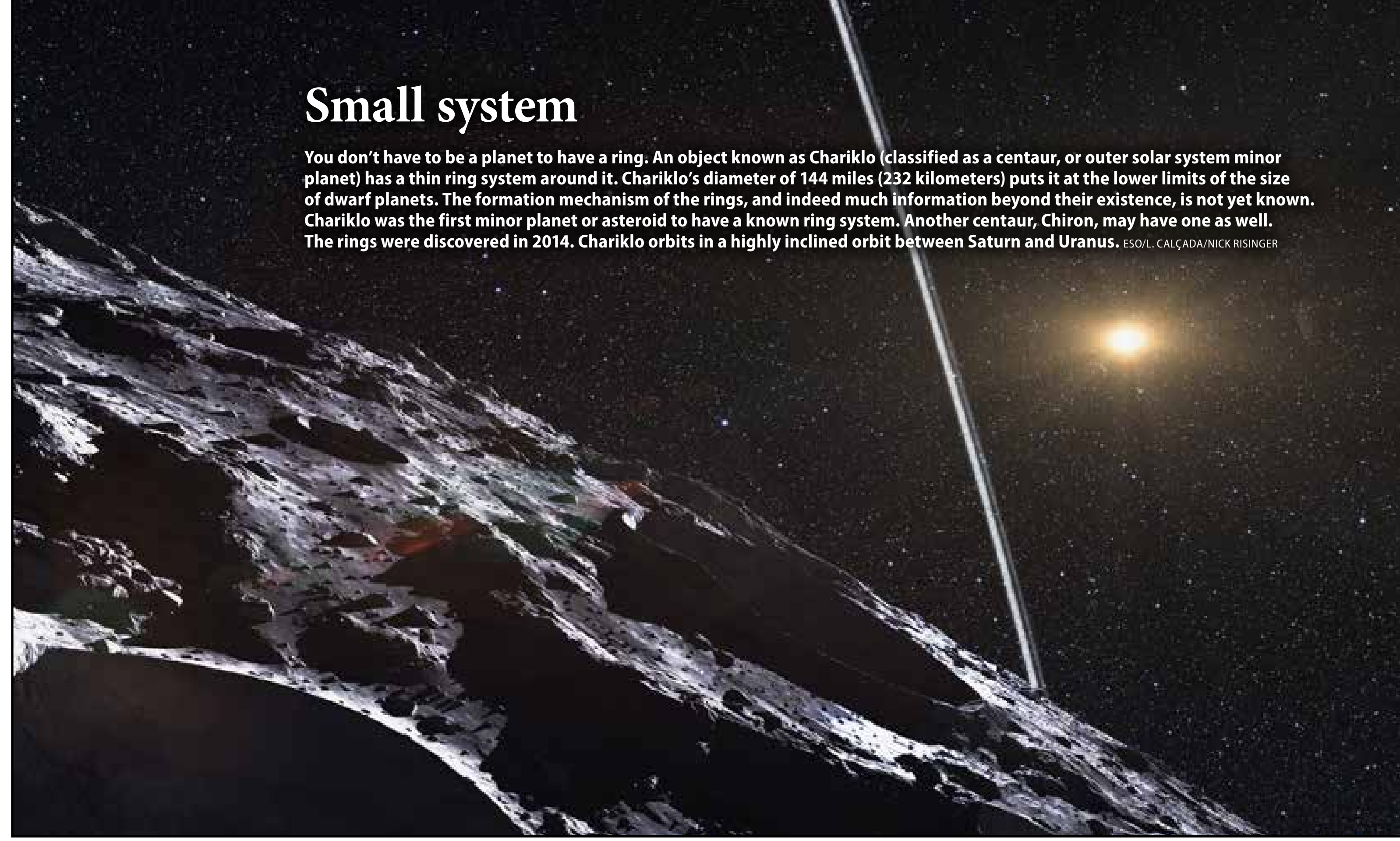
As Phobos reaches its Roche limit, about 3,400 miles (5,470km) from the martian surface, tidal forces will start pulling Phobos apart. Just as Saturn's tidal forces may have peeled away the icy mantle of a Titan-sized moon billions of years ago, the hundred meters or so of regolith will be stripped off Phobos. It will happen quickly: In as little as a week, the dust will spread into a ring circling Mars, the moon no more.

Depending on how much material is stripped off Phobos, the ring could initially have a mass density similar to that of today's rings of Saturn. The martian ring will be very dark, unlike Saturn's bright icy rings, more like the dusty rings of Jupiter that are darker, thinner, and more diffuse. It will practically hug Mars, closer in relative terms to the planet than the other planetary rings in the solar system. And the ring, say Black and Mittal, will not last long; they estimate its lifetime at between 1 million and 100 million years.

Roche limit



As Phobos spirals inward, it will reach a distance, called the Roche limit, where the moon will be pulled apart by Mars' gravity. The end result will be a temporary ring around Mars. *ASTRONOMY*: ROEN KELLY



Small system

You don't have to be a planet to have a ring. An object known as Chariklo (classified as a centaur, or outer solar system minor planet) has a thin ring system around it. Chariklo's diameter of 144 miles (232 kilometers) puts it at the lower limits of the size of dwarf planets. The formation mechanism of the rings, and indeed much information beyond their existence, is not yet known. Chariklo was the first minor planet or asteroid to have a known ring system. Another centaur, Chiron, may have one as well. The rings were discovered in 2014. Chariklo orbits in a highly inclined orbit between Saturn and Uranus. ESO/L. CALÇADA/NICK RISINGER

Eventually, the rocky rubble left behind will meet a quicker but equally dramatic end. It will plummet down along slanting paths to impact the surface of Mars and leave a string of elongated craters along the planet's equator.

Other once and future rings

Is it possible that Mars possessed a ring system in its distant past? "We're not certain," says Black, "but it would be worth investigating whether past inwardly migrating moons may have existed. Some fraction of moons might be expected to have an orbital configuration similar to that of Phobos and Mars."

Some planetary scientists think Mars once did have more than two moons. Researchers have identified 258 elliptical craters on Mars formed by objects hitting the surface at grazing angles. At least some of them could well have been made by oblique impacts of ancient martian moons. If so, others may have broken up before hitting the atmosphere, leaving short-lived rings of rocks and dust around Mars.

Several studies confirm that Phobos' inward spiral will lead to its destruction in 25 to 75 million years.

There's no evidence that Mercury or Venus ever possessed ring systems. Earth did, though, for an extremely brief period during the formation of the Moon 4.5 billion years ago when our planet was struck by a Mars-sized body dubbed Theia. Much of Theia merged with Earth, but the "Big Splash" would have blown the remaining material into space. Computer simulations indicate about 20 percent of Theia's mass would have gone into orbit around Earth as a ring. About 10 percent of the ring's material then quickly coalesced into the Moon, with the rest eventually falling back to Earth. The ring would not have lasted long, perhaps as little as a month but probably no more than 100 years.

Curiously, our Moon also could end as it began, according to astronomer Lee Anne Willson, university professor emerita at Iowa State University. As part of her research on the fate of Earth as the Sun expands into a red giant, she found that the Moon stood a chance of becoming a ring around Earth.

The Moon is receding from Earth at a rate of about 1.6 inches (4cm) per year. Left unchecked, the Moon will eventually migrate out to a distance where it will take 47 days to orbit Earth. By then, Earth's rotation also will have slowed to 47 days. The two will then keep the same face to each other, as Pluto and its moon Charon do today.

Before this happens, though, some 5 billion years from now, the Sun will enter its red giant phase. It will start expanding in size, and swallow up Mercury and Venus. As the Earth-Moon system orbits through the Sun's expanded outer atmosphere, drag forces will cause the Moon's orbit to begin decaying. The Sun probably will continue to expand, and destroy both Earth and the Moon. On the other hand, if the Sun should blow off about 20 percent of its mass first, the Moon will continue to spiral down to its Roche limit. Tidal forces will tear it apart, just as they will destroy Phobos.

And then, 9 billion years after the Moon's birth from a ring of molten impact ejecta, and nearly 5 billion years after the birth and death of the ring around Mars, Earth will once again have a ring.

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